STUDIES IN MHD POWER GENERATION WITH SPECIAL REGARD TO THE INFLUENCE OF HALL EFFECT

INAUGURAL DISSERTATION

BY

ERIK WITALIS
TEKN. LIC.

BY DUE PERMISSION OF THE FACULTY OF SCIENCE OF THE UNIVERSITY OF UPPSALA TO BE PUBLICLY DISCUSSED IN THE LECTURE HALL OF THE INSTITUTE OF PHYSICS ON APRIL 16TH, 1966, AT 10 A. M., FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

NYKÖPING 1966
GUST. ÖSTERBERGS TRYCKERI AB

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Contents

The thesis includes the following papers:

I. WITALIS, E. A.: "Performance of a segmented electrode MHD generator for various electrode-insulator length ratios", Plasma Physics (J. Nucl. Energy, Pt C), 7, 235, (1965).

II. WITALIS, E. A.: "Analysis of linear MHD power generators", Plasma Physics (J. Nucl. Energy, Pt C), 7, 455, (1965).

III. WITALIS, E. A.: "Characteristics of linear MHD generators with one or a few loads", Report AE-214, (1966), also accepted to be presented at International MHD Power Generation Symposium, Salzburg, 1966.

IV. WITALIS, E. A.: "Methods for the determination of currents and fields in steady two-dimensional MHD flow with tensor conductivity", Report AE-210, (1965), also Plasma Physics (J. Nucl. Energy, Pt C), 8, No. 3, (1966).

V. WITALIS, E. A.: "Incompressible steady flow with tensor conductivity leaving a transverse magnetic field", Report AE-209, (1965), also Plasma Physics (J. Nucl. Energy, Pt C), 8, No. 3, (1966).

VI. WITALIS, E. A.: "Voltage limit of a thermally ionized one-dimensional gas discharge", Journal of Applied Physics, 35, 3617, (1964).

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An Introduction to MHD Power Generation

General

The present thesis consists of theoretical contributions to a fairly new technique, the magnetohydrodynamic (MHD) power generation. Though extensive research on this subject has been going on merely during the last six years, it now bears all the signs of an expanding technology with many and highly specialized branches both of experiment and theory.

In order to provide a framework for the thesis, relevant parts of the fundamental theory of MHD power generation will be given in appropriate detail, but without formulas and in the simplest possible terms. Prior thereto some general aspects of new and conventional electrical power generation will inform about incentives and prospects.

References to previous studies are not given here. They, as well as the proper credit to others, can of course be found in the separate papers. It was felt, however, that one outstanding paper should be mentioned here, and that is the work performed in 1961 by H. Hurwitz, Jr, R. W. Kilb and G. W. Sutton. Their paper is not free from defects and has often been said to be hard to penetrate; still it fully deserves to be called a pioneering achievement. The first paper of the present thesis originated from a study of their work.

Present and future electrical power generation

Large-scale electrical power is at present obtained entirely by the combined action of two basically simple devices, both of which operate with rotating components. They are the turbine and the a. c. generator. The real arrangement, however, is now a highly sophisticated machinery of which almost each detail is the result of inventions and many improvements. In the same way, systems for power transportation and distribution have continuosly advanced. The outcome of this is a highly refined product with the common name "current", and it is supplied with such perfection that almost everyone has become utterly dependent upon it and takes its permanent presence for granted.

In view of these rather obvious facts, any new device for the production of vast amounts of power must of course operate, and operate very efficiently, in quite a different way, so as to remove some fundamental limitation or defect inherent in the well established method. The main limitation concerns turbines. They have to be built to withstand extreme stresses in

the parts which rotate at high speeds and temperatures; and, in spite of recent and advanced constructions, it does not seem likely that their performance can be enhanced very much at a reasonable cost. In order to clarify this bottleneck in conventional power production, a few words may be said about power demands and sources.

The demand for power seems to increase at about the same rate as added power becomes available, and this exponential increase has made the hydroelectric power plants insufficient. Electricity has then to be generated in thermal and atomic stations using fossil and nuclear fuels, respectively. In both cases high quality steam is the working gas in the turbines. The overall cycle efficiency for modern plants of these kinds is about forty per cent. This figure may seem modest, but actually is very close to what can theoretically be expected from advanced engineering applied to systems with turbo-generators. If, instead, the output power was extracted partly by the unconventional MHD generator, it is estimated that the same efficiency could be raised by more than ten per cent. This does not mean that the new generator will sooner or later render the older one obsolete; on the contrary, their combination appears to be attractive. The MHD generator would then "top" a conventional station by operating in a high temperature region where turbines would fail.

It should be stated here that the MHD generator is inherently a d. c. device. Schemes for a. c. power generation have not yet proved feasible. It is also quite capable of high voltages but will probably operate efficiently only in the case of large-scale power production. At present only half-scale test plants are operating, except for generators for special military purposes requiring very large amounts of power during a short time.

Working principles of the MHD generator

The idea of the MHD generator is deceptively simple: in reality its highly interdependent mechanical, thermal and electrical effects make it a highly complex machine.

The starting point is the energy source, where chemical or fission energy raises the total heat content of the working gas, wich usually is simply taken to be combustion gas or the reactor cooling medium. The heat content is then partially converted to directed kinetic energy by an adiabatic expansion of the gas in a nozzle before it enters the MHD generator region. The gas must there be ionized, i. e. electrically conducting, not the same extent as copper or carbon but preferably better, for instance, than saturated salt water. How to achieve this conductivity is at present the largest subject for MHD power generation research. A few rather special aspects on one method are

treated in the last paper of the present thesis, but, apart from that, lack of space prevents a discussion of the very intricate techniques for making the gas sufficiently conducting.

The MHD generator itself is a simple and old cencept in which the copper conductors of the conventional generator are replaced by the conducting expanded gas. When the gas moves in a direction perpendicular to an applied magnetic field, an electromotive force is induced in i which is proportional to the product of the gas velocity and the magnetic field strength. If electrodes are placed in the flow and connected by external loads, then the electromotive force will make current flow through the gas and via electrodes to the loads, and electrical energy is extracted. The working principle is just an example of Faraday's induction law. He is also claimed to be the inventor of the MHD generator. His plan was to use the motion of salt water caused by the tides as it cut the earth's magnetic field to generate power.

MHD power generation is often referred to as a method of direct conversion. Actually, it is very little related to real direct conversion devices like the fuel cell. Instead, the MHD generator may be considered as a combination of the turbine and the generator. It extracts energy by braking an expanded gas flow like a turbine does, but it also converts mechanical energy into electricity like a generator. Only to the extent of this double action should it be called a direct conversion device.

In the sequel it will be shown that fundamental differences exist between conventional and MHD power generation, and analogies should be used with care. The electrodes in the MHD channel, for instance, are sometimes translated into the commutator brushes of conventional generators. This is not correct, because brushes usually provide magnetization current which, in case of MHD generators with power-consuming magnets, is normally thought to be supplied independently of the electrode currents.

After the MHD power has been extracted, the gas will still have considerable enthalpy, and it can be used in a preheater or led via a diffuser to a conventional steam turbine cycle. Combustion gases will finally be discharged, i. e. they are used in so-called open cycles, in contrast to the closed cycle where a reactor heats the gas again.

It can be concluded that the MHD generator solves the problem of power conversion at very high temperatures, and this because the conversion process is entirely confined to the hot gas. The solid parts of the generator need not be hot, highly stressed or machined to close tolerances. Hence the generator can withstand thermal stresses, erosive and corrosive atmospheres, and temperatures, which would destroy any other conversion device in a very short time.

Properties of MHD generator gases

The requirement that thermal energy be transformed into kinetic energy implies that the only suitable working fluids are gases.*) But gases are difficult to make electrically conducting, and those wich are favourable in this respect unfortunately exhibit a comparatively large resistance to motion of charge carriers. The inevitable low conductivity, therefore, requires the power-producing gas volume to be many orders of magnitude larger than the copper conductor volume of the conventional wire-wound generator. Also, the applied magnetic field will be very little disturbed by the gas current.

In the presence of a magnetic field the conductivity of a gas becomes anisotropic, so that it is no longer a scalar but a so-called tensor. This phenomenon, caused by the Hall effect on the charge carriers, is hardly noticeable in a metallic conductor, but strongly pronounced in ionized gases, and is fundamental for both theory and performance of MHD power generators.

There is little reason to give a strict derivation of the Hall effect in this survey. The overall result, however, is that the current is no longer in the direction of the electric field but inclined at an angle to it. This angle is not small, in fact there are generator concepts according to which the current component perpendicular to the electric field is taken to be an order of magnitude larger than the parallel one. The ratio of perpendicular to parallel conductivity is given by the Hall parameter, which can also be defined as the product two quantities. Two alternatives of the definition exist, either the magnetic field strength times the electron**) mobility, or, the electron gyration frequency in the magnetic field times the mean time between consecutive collisions between an electron and the gas atoms. The first alternative indicates that an appreciable Hall effect has to be present because, obviously, neither of the two factors must be very small. The second alternative concerns the microscopic interpertation of the Hall effect, which is that the magnetic field makes the electrons tend to move in so-called cycloid or trochoid paths perpendicular to the electric field but the collisions limit that motion and make a concurrent parallel motion possible.

Segmentation and connection of electrodes

The charged particles in the moving gas experience the net action of the induced and the static electric field. The former is directed at right angles to the flow direction and the magnetic flux. As in all generators, the two fields

*) We here disregard schemes based on mixtures of fluids and gases.

**) The charge transport by ions is generally small and is disregarded in this survey.

oppose each other, and the current flows against the static field. If the gas conductivity was very high the two fields would almost cancel each other, as they do in a conventional wire-wound generator. However, the induced field must here be considerably larger than the static in order to achieve any reasonable current density.

In the absence of Hall effect, the current would follow the induced field right across the gas flow, and two parallel and opposed plane electrodes would suffice. An intermediate or strong Hall effect drastically changes the situation. Then, the charge carriers will no longer follow the transverse field, and a longitudinal current component in the direction of gas flow appears. It will cause the gas current to flow mainly from the downstream-end edge of one electrode to the upsteam-end edge of the other. Very large ohmic power losses are associated with such current concentrations, and the concept of electrode segmentation was introduced as a method of minimizing them. Each of the two continuous electrodes is then substituted by many adjacent and axially narrow electrodes, i. e. is split up into conducting ribbons or segments insulated from each other and directed along the magnetic field. The single external load is replaced in the same way by many loads, each of them connecting a pair of opposed and thin electrodes. Then, except very close to the electrode surface, the gas current from an electrode is forced to flow transversely to the opposite one. The total current concentration losses are made much smaller, but this occurs at the expense of an increased number of loads.

The effect of segmentation may equally well be explained as caused by a longitudinal electric field, the Hall field, wich prevents the current from flowing along the generator. Very close to an electrode this field is shorted out and the current concentrations as described above will exist. The electrode can also be said to provide a return path for eddy currents induced by the Hall field in its vicinity. The general expression for these phenomena is "finite electrode size effects".

The existence of the Hall field proves that adjacent electrodes will attain different potentials. This suggests a profitable idea: why not try to connect them in some way so that one or a few loads replace all the others? Such a "cross-connection" can indeed be performed, and in fact it is the Hall effect wich enables a MHD generator to deliver all its electrical power at a high voltage into one single external load.

Summary of Papers Included in Thesis

I. *Performance of a segmented electrode MHD generator for various electrode-insulator length ratios*

This paper treats the influence of the relative size of the electrodes and the insulating gaps between them. Consideration was given only to the generator type wich has separate loads and the electrodes placed so that the current direction in the channel centre is perpendicular to the gas flow. However, the results obtained can very well be applied also to cross-connected generators with one or a few loads.

Problems in which the Hall effect is important usually require special techniques. Conformal mapping was used here in accordance with a previous work referred to. This, however, considered only equal electrodes and insulators. In order to make the problem tractable, considerable simplifications were necessary. Thus the conformal technique requires a periodically repeated but otherwise constant MHD duct geometry and, furthermore, uniform plasma properties and perfect electrodes and insulators.

Rather little attention had previously been given to the electrode-insulator length ratio problem. It was known, however, that the insulating gaps should not be too small, because this would lead to current leakage between adjacent electrodes. Also, the current concentrations as described needed further investigation. As a consequence, for example, of the very narrow effective electrode area, it had been suggested that the electrodes be replaced by wires in case of difficulty of insulation. This change did not prove to affect the current flow pattern very much.

The relevant conformal mapping function was derived by applying a Schwarz-Cristoffel transformation to the electrode wall. The conformal representation of the entire channel was then studied, and the field and potential distributions were found. The invariance of electrode currents and potentials led to a simple interpretation of the finite electrode size effects: they can be attributed to a fictitious increase of channel width with a subsequent increase of generator internal resistance.

When studying the transformation function properties, the condition for internal current leakage came out in an exact and graphic way. It was proved analytically that the internal resistance of the generator attains a minimum when the electrode-insulator ratio is so large that leakage currents almost start to flow. The proof, as well as come other important calculations, could not be included in the paper because of their length. A number of curves obtained from computer calculations give the general dependence of generator performance on electrode size and Hall parameter. Also,

the idea of wire electrodes was proved to be wrong. Such electrodes would indeed lead to an almost unchanged current flow pattern, but to an unfavourable potential distribution causing a large internal resistance.

II. *Analysis of linear MHD power generators*

The author considers this to be the main work of the present thesis. It may also represent a proof of the power of the conformal technique.

As in Paper I, an infinitely long power generating duct was considered, but here no restrictions were placed on the generator design and circuitry except those listed above as necessary for the conformal mapping of a MHD channel. The effect of ion motion could easily be accounted for by proving that it effectively corresponds to a fictitious reduction of the electronic conductivity.

A general transformation function was derived and presented in somewhat greater detail than in the previous paper. But, here again, extensive numerial calculations and proofs had to be excluded for lack of space. The general expression for the most favourable electrode-insulator length ratio was deduced and shown, in practical cases, to differ insignificantly from unity.

The treatment was made applicable to all possible linear generator types by avoiding any restrictions on the current flow pattern. Instead, the relative position of two short-circuited electrodes was treated as a known constant or a variable.

There has often been discussion about the best relative position for two electrodes with total gas current connection. The two alternatives are, usually, either a shifted position, so that the current flows straight across the channel axis, or an exactly opposed position implying an axial component of the channel centre current. The present analysis has proved that the second alternative should be preferred, because it leads to minimum internal resistance. Unfortunately the mathematical analysis became considerably more complicated in this second favourable case.

In the sequel different generator properties and characteristics were evaluated and presented in a large number of diagrams. They were obtained from almost a million computer-calculated data. Special consideration was given to axial power extraction generators with a single external load. It was proved, for example, that the performance of the so-called Hall generator can indeed be exceeded by generators with more proper short-circuiting.

In the last two sections the assumption of a very long channel was relaxed, and the implications of current flow between a finite number of electrodes were studied. Attention was given only to the optimum case when the gas current flows between identical and opposed electrodes in generators with

one, two and three external loads. It was proved that the power output would then be the same as that from the corresponding generator having many independent loads and operating at the same efficiency.

III. *Characteristics of linear MHD generators with one or a few loads*

This paper is chiefly an extension of the previous work and, in particular, the last two sections of it.

Most experimental and theoretical studies of MHD power generators have been devoted to the type which has many independent loads consisting of identical resistors which can be varied in unison from zero to inifinity. Such an external circuitry is the simplest possible and is probably that which is best suited to basic experimental generator research. However, future power-producing generators must necessarily bè cross-connected and preferably have only one external load, i. e. they must be of the axial power extraction type.

In the present work both the above generators were shown to represent extreme cases of a more general transverse power extraction generator which has identical external loads operating in parallel, each of the loads being connected to a number of series-connected electrode pairs. It was shown how all relevant electrical properties can be calulated when four basic quantities are prescribed. They are the gas Hall parameter, the degree of segmentation, the number of so-called design loads, and the relative position of short-circuited electrodes. Special consideration was given to the influence of variations of the last quantity.

The electrical terminal characteristics, i. e. the full current-voltage relation, can in general not be obtained by the exact analytical method, which is strictly applicable only to design load conditions or infinitely long MHD channels. However, it was shown how the working properties of a finite length channel can be explained and calculated with good approximation by describing its operation in terms of a fictitious "effective" number of external loads. This number does not need to be an integral; in fact, accelerators and electromagnetic brakes could readily have been investigated if the analysis had been extended to comprise negative values of that number.

IV. *Methods for the determination of currents and fields in steady two-dimensional MHD flow with tensor conductivity*

This paper treats the straight channel flow of an incompressible but viscous fluid with uniform tensor conductivity when an external magnetic field is applied perpendicular to the flow direction. This arrangement is, of course, fundamental for most MHD power generation concepts; still a detai-

led examination of possible two-dimensional analysis methods does not seem to have been carried out before. This fact is probably due to the difficulties arising from the tensor conductivity.

In the usual way, the basic equations were given and pertinent simplifications were discussed. A linear and inhomogeneous partial differential equation governing the induced magnetic field was then derived. Although the derivation was rather straight-forward, the equation does not seem to have been used before. There were shown to be some advantages by analysing in terms of the induced magnetic field distribution. First, the interaction between fluid motion and magnetic field need not necessarily be small, i.e. the magnetic Reynolds number can be taken to be arbitrary and, second, the externally applied field does not need to be constant. The difficulties mainly concern proper boundary conditions, and these were discussed. The practical applicability of the induced magnetic field analysis was later proved in Paper V.

The equations for the potential distributions either in the laboratory system or in the moving gas frame, have both been used in previous studies. They were derived in detail, and hence the relevant sets of suitable simplifications, restrictive conditions and boundary considerations could readily be given. Finally, a survey was presented of previous investigations.

V. *Incompressible steady flow with tensor conductivity leaving a transverse magnetic field*

This is an investigation of interaction phenomena occurring when a tensor conducting plasma flows through the termination of a magnetic field perpendicular to it. Ohmic power losses and other effects associated with this problem have been regarded as of central importance for the performance of MHD generators, and a fairly large number of papers have been devoted to it. Most of them are hardly realistic, because the Hall effect is neglected. Those which do consider it are based upon the restrictive assumptions necessary for a potential distribution analysis.

The physics involved in the present problem is easily described. A strong electric field is induced in the conducting gas flow within the applied magnetic field region. Outside, it is almost absent and there the plasma has a short-circuiting action on the induced electric field. An eddy current system arises, and this was investigated. The magnetic field distributions inside and outside the applied field were expressed in Fourier series, and the pertinent conservation laws for current and electric field were applied to the transition. This led to infinite equation systems for the Fourier components. They were solved approximately on a computer, and the spatial distribution of the induced magnetic field and ohmic power loss, both pa-

rallel and transverse to the flow, could then be given as functions of the Hall parameter with consideration also to the magnetic Reynolds number of the gas flow. It was found that the total losses decrease very much with increasing Hall parameter, but a more striking feature was the strong axial contraction of the loss region. Especially for intermediate values of the Hall parameter an appreciable ohmic loss in an axially very narrow region was found; still this region had a fairly uniform distribution across the flow. These facts may be important for the design of the inlet section of a MHD generator operating with so-called non-equilibrium ionization. The strong electrical fields involved in the intense power dissipation would then increase the electron density, and so also the gas conductivity.

VI. *Voltage limit of a thermally ionized one-dimensional gas discharge*

This paper is a short study on the thermal effect of cold electrodes on the electric field distribution in a thermally ionized, quiescent discharge.

In connection with experiments with thermal ionization, current-voltage characteristics of diodes with plane electrodes have often been reported. Usually they exhibit a voltage limit, i.e. when the current is large enough a further increase of the current causes no, or a very slight, voltage increase. This non-linearity had previously been explained in different ways such as changes of the cathode mechanism or electron heating. A simpler and more likely explanation is found when the extreme temperature sensitivity of the plasma conductivity is observed. It was proved that the limiting voltage could be explained and calculated simply as a consequence of the thermal effect of the electrodes on the electric field distribution. The theoretical model was later verified experimentally.

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Erik Witalis